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Power Quality Concerns in Implementing Smart Distribution-Grid Applications

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***Abstract*— This paper maps the expected and possible adverse consequences for power quality of introducing several smart distribution-grid technologies and applications. The material presented in this paper is the result of discussions in an international CIGRE-CIRED joint working group. The following technologies and applications are discussed: microgrids; advanced voltage control; feeder reconfiguration; and demand-side management. Recommendations are given based on the mapping.**

***Index Terms* — Conservation voltage reduction (CVR), demand-side management (DSM), feeder reconfiguration, microgrids, power quality (PQ), smart grids, volt-var control/optimization (VVC/VVO).**

I. Abbreviations

AC – Alternating current
ADA – Advanced distribution automation
CFL – Compact fluorescent lampts
CRT – Cathode-ray tube
CVR – Conservation voltage reduction
DC – Direct current
DER – Distributed energy resources
DSM – Demand-side management
EMC – Electromagnetic compatibility
EMI – Electromagnetic interference
EV – Electric vehicle
FDIR – Fault detection, isolation, and restoration
FLISR – Fault location, isolation, and restoration
HFAC – High-frequency AC
HV – High voltage
LCD – Liquid crystal display
LED – Light emitting diodes
LFAC – Line-frequency AC
LV – Low voltage
MV – Medium voltage
OLTC – On-load tap changer
PFC – Power factor correction
PQ – Power quality
PWM – Pulse-width modulation
RVC – Rapid voltage change
VVC – Volt-var control
VVO – Volt-var optimization

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II. Introduction

SMART distribution-grid applications have the potential to improve the performance of the electric power system, as well as to offer the same performance as existing technologies, but in a more cost-effective way. This holds for power quality (PQ), as well as for other aspects of the system performance. The introduction of smart distribution-grid applications, without dedicated mitigation measures, might however have adverse consequences for PQ unless managed.

In the context of smart grids, the primary determinants of complex supply-demand interactions are the changes in the actual amount and form of power flows and energy exchanges between the "supply-side" and "demand-side". On both sides, the changes in the basic principles of operation, which are already taking place in existing networks, will only be more pronounced in the future. These changes are characterized by a shift from unidirectional power flows primarily in an alternate current (AC) system to bi-directional power flows in both direct current (DC) and AC forms in much wider frequency ranges. Maintaining sufficient PQ levels in an evolving network remains a critical task, particularly to maintain a high probability of electromagnetic compatibility (EMC). The key indicators and metrics provided by PQ monitoring describe and quantify the compatibility between the grid, i.e. "supply side", and customers' equipment, i.e. "demand side". Thus, PQ is an important tool when analyzing the effects of these interactions and changes expected to arise in future grids.

Improved PQ performance is one of the basic aspects of future electricity networks. Smart-grid technologies have a large potential of achieving this. However, the introduction of smart grid technologies will also result in increasingly complex electricity networks, featuring significantly higher penetration levels of distributed energy resources (DER) (e.g. renewable generation and storage), introducing new intelligent and flexible monitoring, communication and control systems and incorporating various demand-manageable resources. The levels and nature of supply-demand interactions in future electricity networks will change, shifting the actual system operating and loading conditions well outside the traditionally assumed ranges, limits and physical boundaries. When not managed correctly, this might actually result in a deterioration of PQ performance levels in smart grids, where of particular concerns are increased dynamics of two-way power flows, higher harmonic emissions, dc offsets and unbalances, as well as more frequent occurrence of voltage variations, switching transients, voltage sags/swells and momentary/short interruptions. Equally important issues are increased sensitivity of customers' power electronic equipment and their interference with power line carrier signals and other grid-connected equipment.

This paper gives a review of the ways in which smart distribution applications are expected to adversely impact PQ. It combines the state-of-the-art with expert knowledge and insight and discusses and gives a mapping of the expected and potentially adverse consequences of four different applications: microgrids (Section IV); advanced voltage control (Section V); feeder reconfiguration (Section VI); and demand-side management (Section VII). The mapping is to a large extent based on the experience and knowledge of power quality and smart grid experts in an international joint working group: CIGRE/CIRED JWG C4.24 (see Section III). The paper also presents available information from other publications and some experience from field experiments. Recommendations based on the mapping are presented in Section VIII, for a number of PQ disturbances. For background and details on those disturbances, the reader is referred to the general literature on power quality [1,2,3].

III. CIGRE/CIRED Joint Working Group C4.24

CIGRE/CIRED Joint Working Group C4.24, "Power quality and EMC issues associated with future electricity networks" (C4.24 in short) is a joint working group of CIGRE and CIRED, that operates in close cooperation with an IEEE working group covering the same subject. C4.24 obtained its mandate in 2013 and is expected to deliver its final report in 2017. The scope of C4.24 includes, among other aspects, study of the "*positive and negative impact of new smart distribution applications on power quality in the distribution grid*".

IV. Microgrids

Microgrids are electricity distribution systems containing controllable loads and DERs that can be operated in a safe, secure and coordinated way when either connected to the main power network, or disconnected from it (so called "islanded operation").

Microgrids offers distinct advantages to customers and utilities: improved energy efficiency, minimization of overall energy consumption, reduced environmental impact and improved reliability of supply, for the former, as well as loss reduction, congestion relief, voltage control, or security of supply and more cost-efficient electricity infrastructure replacement, for the latter. Microgrids have therefore been proposed as novel distribution network architecture within the so called smart grid concept, capable to exploit the full benefits from the integration of a large number of small to medium DERs (less than around 1 MW) into LV and MV electricity distribution systems. There are three major objectives/benefits of microgrids [4]:

- To provide power quality and/or reliability levels different from the local standard of service, e.g. to serve particularly sensitive loads, such as emergency services;
- To use local assets which would otherwise unlikely be chosen, or difficult to integrate by the centralized grid, e.g. small-scale renewable resources, or electric vehicle (EV) batteries as storage in vehicle-to-grid applications;
- To present controlled supply-demand profiles to the wider power system, e.g. to balance local renewable resources and reduce their negative impact on the grid.

Microgrids can be classified according to the type of power distribution: DC microgrids, High-Frequency AC (HFAC) microgrids, Line-Frequency AC (LFAC) microgrids, and hybrid DC and AC-coupled microgrids [5]. The LFAC type is the most common, the DC concept has been applied in telecommunication systems and EV charging stations, and HFAC is used for marine and aircraft power distribution systems (400 Hz). In this paper, only the LFAC and the DC microgrid will be discussed.

A. PQ Concerns in LFAC Microgrids

In LFAC microgrids, the DER devices are typically interfaced to the grid via a power electronics interface, with the exception of conventional rotating machines. In such cases, it is possible to have both directly connected, as well as power electronic interfaced devices. In some microgrid design philosophies, regardless of the type of DER, all devices are connected via power electronics for improved control of fault current, droop response, etc. The Consortium for Electric Reliability Technology Solutions (CERTS) microgrid, for example, is an "all power electronic interface", whose potential applications include industrial parks, commercial and institutional campuses and other locations that require uninterrupted and high power quality electricity supply [6].

From a PQ perspective, microgrids are operated in two distinctive modes: grid-connected and islanded. The adverse impacts on PQ are expected during islanded operation, but also during the transitions between islanded and grid-connected operations. These transitions may make some DER units to switch from voltage controlled mode (during islanded operation) to current controlled mode (during grid-connected operation), causing voltage stability problems due to the delay in detection of non-intentional islanding.

In islanded mode, higher dynamics and wider ranges of interactions between microgrid loads and available small or medium-scale DERs will result in more pronounced, more frequent and longer voltage and frequency variations, This will be further augmented by the reduced short circuit power and inertia of microgrids.

The power electronics interfaces of DER connected to the microgrid include traditional grid-commutated topologies, which might cause undesirably high levels of harmonics when they are connected to the power grid. Self-commutated PWM

(Pulse-Width Modulation) controlled inverters typically produce supraharmonics (waveform distortion in the range from 2 kHz to 150 kHz) [7].

For the static performance of microgrids, the low X/R ratio of distribution line impedance might affect the load sharing accuracy of inverters, typically resulting in unbalances. Furthermore, harmonics and unbalances are poorly compensated with the connection of nonlinear and unbalanced loads. For the dynamic behavior of microgrids, the voltage and frequency dependencies of load responses have to be taken into account when choosing droop characteristics for DER units; otherwise, controllers may fail to ensure a proper sharing and lead to instability [5].

B. PQ Concerns in DC Microgrids

Recently, DC microgrids have been increasingly explored with the goal of more efficient integration of DER devices, including energy storage, and non-linear loads through the elimination of some rectification and power inversion or conversion stages.

The PQ issues in DC microgrids are related to differences between the ideally constant voltage in a DC system and the actual voltage provided by power electronic converters. Four fundamental PQ concerns have been identified in DC microgrids [8]:

a) waveform distortion in DC systems is associated with the presence of current and voltage oscillations (steady-state non DC components), which can be considered similar to AC harmonics. The control of harmonic currents drawn by a load converter, or the voltage ripple produced by a DER converter is achieved using EMI (ElectroMagnetic Interference) filters, which are usually placed at the connection with the DC bus.

b) the capacitance of EMI filters can draw a substantial inrush current when a load connected to the DC system is switched on, causing voltage oscillations at the point of connection of the load. When they exceed the operating voltage range, some loads may be switched off [9].

c) faults occurring on DC systems are supplied through DER converters and limited by the converters' power ratings and associated protection/control circuits. To increase fault currents to the values that will trip the system protection, the EMI filter's capacitance needs to be increased, which will then imply higher inrush currents.

d) the choice of an appropriate grounding configuration for a DC distribution system has an impact on the power quality and safety, particularly during faults. The type of grounding will determine the path of current for a ground fault and impact the level of fault current, including electric shock hazard of a person in contact with affected fault circuit.

C. PQ Concerns with External Origin

The analysis of PQ disturbances can be broken into those originated from outside of the microgrid (external) and those originated inside the microgrid (internal) [9]. During islanded operation, there will be only disturbances with internal origin.

A microgrid has the possibility to transfer to islanded operation during a severe external disturbance. A sustained (long) interruption is the most common example, but islanded operation can be initiated also due to momentary (short) interruptions or voltage sags (dips). Islanded operation is also possible during periods with a higher risk of disturbances, like thunderstorms in the neighborhood, resulting in a high risk of voltage sags.

During the initial stages of a transfer to islanded operation, triggered by an interruption or sag, equipment connected to the microgrid will still see a disturbance. The interruption or sag will be shorter, but will not disappear completely. A DC microgrid has better possibilities for reducing the severity of the remaining disturbance than an AC microgrid.

Overall, for PQ disturbances that originate outside the microgrid, a DC architecture has a distinct advantage over an AC architecture. It has also the potential to improve PQ for faults inside the microgrid [10].

V. Advanced Voltage Control

A. Drivers

The voltage control or volt-var control (VVC) in the future grid is expected to be significantly different than it is today. The main driving force behind this, especially in Europe, is the ongoing or expected large-scale introduction of solar power in the distribution network. Changes on demand side will also contribute to the changes in voltage control, e.g. the introduction of electric heat pumps replacing gas heating; plug-in electric vehicles, participation of load in short-term (one hour and less) electricity markets and distribution customers providing reactive-power support to higher voltage level.

B. Ongoing and Expected Developments

The two main developments in distribution voltage control are: conservation voltage reduction (CVR) and distribution transformers with on-load tap changers.

a) CVR aims at reducing electricity consumption of low-voltage customers by reducing supply voltage [11]. A range of North American utilities have such schemes in operation, whereas many others are planning the implementation. With CVR, the voltage in the distribution network is kept as low as possible, but without exceeding the lower limit of the allowed voltage variations. The implementation typically involves on-load tap changers (OLTCs), voltage boosters and capacitor banks, but future schemes will likely involve DER as well. The term "volt-var-optimization (VVO)" is often used in this context, especially when loss minimization is one of the objectives.

b) Distribution transformers with OLTC are considered by several European network operators to cope with the high amount of solar power and future increase of heat pumps and EVs [12-16].

Although there is no indication yet of network operators implementing some of the advanced optimization schemes discussed in recent literature [17-21], the availability of modern monitoring, control and communication equipment makes such schemes within reach of existing technology. Practical implementations will likely include customer-side inverters and grid-based power electronics in the control.

C. Potential Impact on Power Quality

The overall impact of advanced voltage control on voltage quality will be positive, as voltage magnitudes will vary less. However, there will be adverse impacts as well, which can be either traced back to the control algorithms having their limitations, or to the specific types of the implemented voltage-control methods.

Where it concerns the impact of the method on PQ, two fundamentally different cases should be distinguished: discrete control (e.g. by OLTC transformers and switched capacitor banks) and continuous control (e.g. by static compensators).

1) Slow voltage variations

When the voltage control is based on HV/MV OLTC transformer, the voltage behind individual distribution transformers may be out of the acceptable range. This could especially be a concern with CVR, where the voltage is maintained close to the lower voltage limit [22-24].

A study based on 57 low-voltage feeders in the UK [22] investigated the probability that the customer voltage is outside of the regulatory limits. To maintain this probability below 1%, the voltage on the MV side of every MV/LV transformer should be maintained between 0.94 and 1.1 pu. However, if a value of 5% non-compliant customers is acceptable, a wider voltage range from 0.91 to 1.1 pu could be considered. This indicates limits to the use of CVR without active voltage control in the distribution system.

2) Short-duration undervoltages

The CVR might result in an increase of the number of short-duration undervoltages. Taken over one to ten minute windows, the voltage magnitude will be acceptable, but closer to the lower limit. However, at shorter time scales, the voltage magnitude might exhibit deeper and more frequent excursions across the undervoltage limit.

Very limited actual data on this is available and a study [25] showed that the risk of undervoltages is very low when using CVR. The field measurement also showed that there would be at most a small increase in number of equipment trips related to voltage sags. It is unclear if this is valid for other locations and for longer monitoring periods.

3) Rapid voltage changes

Discrete control methods will result in an increased number of voltage steps ("individual rapid voltage changes") and an increase in flicker severity.

Studies presented in [14,15,26] show that the number of tap changes can vary a lot depending on the used control algorithm. The study in [14] predicts between 136 and 467 switching actions per year, i.e. on average 0.4 to 1.3 per day. The actual numbers may, however, show a strong day to day variation. The risk of increasing ageing due to a high number of tap changer operations was mentioned in [27, 28], but not in relation to power quality. Whereas the average over a longer period matters for ageing, the highest number during a one-day period, matters for power quality. In [28], the number of tap changes is calculated for a day in July with changing cloud cover. With a 1-min averaging for the voltage control, up to 80 rapid voltage changes can occur in a single day. However, using 30-min averaging will bring this down to 10 events per day.

The magnitude of the rapid voltage changes will be determined by the steps in the tap-changer. Different manufacturers and publications give different values. The value of 2.5% has been traditionally used for the off-load tap changers and this value is used also for on-load tap changers, for example in [25]. But values of 2% are mentioned in [13, 15].

4) Harmonic distortion

Using switched capacitor banks will introduce harmonic resonances that will change whenever a capacitor is switched. Using many small banks will introduce a large number of possible resonance frequencies, resulting in a likely amplification of harmonic emission over a wide range of frequencies.

There is a strong relation between the resonant frequency and voltage step due to switching the capacitor, assuming that the switched capacitor is the main source of capacitance at the switching location. A resonance frequency at 7^{th} order harmonic corresponds to a voltage step of about 2%, for 5^{th} harmonic to 4%; and a step of 6% corresponds to a resonance frequency around 4^{th} harmonic. As 5^{th} and 7^{th} harmonics are the dominating ones at distribution level, any voltage step of 2% or higher due to capacitor bank switching introduces a serious risk of high distortion due to resonance.

Most of the continuous control methods use power-electronic converters that introduce harmonics into the grid. Especially an increase in the emission of supraharmonics is expected [29].

5) Switching transients

Using switched capacitor banks will introduce switching transients; using multiple banks will also introduce back-to-back switching transients that have a much higher oscillation frequency and where amplification of the oscillations may occur. The magnitude of the capacitor energizing transient depends strongly on the amount of damping present in the network. Earlier measurements have shown overvoltages up to 1.5 to 1.8 times the pre-event voltage magnitude during the switching of individual capacitor banks [30]. For certain combinations of resonance frequencies in systems with multiple capacitors, the magnitude of the energizing transient can be much higher than normal and values up to 4 pu have been measured [30]. However, these measurements did not concern VVC schemes, so it is not known if those high overvoltages can also occur in these cases.

Finally, recent measurements ([25]), specifically related to energizing of capacitors as parts of a VVC scheme, showed overvoltage up to only 1.2 times the pre-event voltage magnitude. Further studies are needed to decide to which extent capacitor-energizing transients could be a concern. Additionally, more information on damping of switching transients in distribution networks is needed.

VI. Feeder Reconfiguration

The radial system is the most common distribution network configuration due to simple operation practices and efficiency in serving many loads. The requirements for improved reliability in smart grids resulted in a "mesh" or "loop" distribution network design. A mix of existing radial feeders and new ties between substations and feeders is increasingly used for improved reliability, even when operated in a radial mode, as it provides a way to reroute power around a faulted section, keeping as many customers as possible in service while the faulted section is repaired [31].

A. Feeder Reconfiguration Following a Fault

With the introduction of modern communication technologies and increased use of automated switches and reclosers in recent years, it is possible to locate and isolate the faulty part or section of the network very quickly. The corresponding features are known as "fault location/detection, isolation, and (service) restoration (FLISR/FDIR) [31, 332]. These are part of advanced distribution automation (ADA) technologies, with the ability to restore service quickly and reduce the number and duration of sustained interruptions, but often resulting in increased number of momentary interruptions, possibly affecting some of the customers [33]. With some schemes (including the classical "autoreclosing scheme with fuse saving"), the resulting number of momentary interruptions is higher than the original number of sustained interruptions [34]. This may be experienced as a deterioration of the supply quality for some customers, but as an improvement by others. Future ADA may require reduction of momentary interruptions as a consequence of their inclusion in regulatory frameworks.

B. Feeder Reconfiguration during Non-Fault Situations

Two main aims of feeder reconfiguration during normal operation are to reduce network losses and balance loads, which are more complicated with the addition of DERs [35]. The stochastic nature of e.g. PV systems at the distribution level requires closer control of active and reactive power flows, so that PQ is managed within stipulated limits [31].

C. Impact on Power Quality

Generally, automatic feeder reconfiguration has a larger impact on PQ (e.g. increase of short interruptions), while manual reconfiguration mostly affects reliability (e.g. sustained interruptions).

1) Supply voltage variations

Switching actions, particularly if they cause momentary interruptions during the transfer, may result in voltage variations over a wider range in a relatively short period of time. This could also result in changing voltage unbalance. Reconfigurations due to faults may also cause the disconnection of major loads, significantly affecting the voltage regulation in both MV and LV networks. In a future grid, disconnections may not be a problem if DERs are able to provide higher levels of fault ride-through tolerance. However, in a network with high DER penetration, it is possible that some of the DERs are disconnected following a fault. During periods of high generation, these multiple disconnect and subsequent reconnect events may cause voltage fluctuations beyond the normal regulation ranges.

2) Supply voltage unbalance

In systems with VVC or other active voltage regulation devices, there may be a period of time when the changes in voltage levels and the voltage unbalances could be quite dynamic.

3) Rapid voltage changes (RVC) and flicker

The transition from one switching arrangement to a different one may yield rapid changes in the RMS voltage in the MV and LV networks. This would impact the *short term flicker perceptibility value* (P_{st}). When there is more than one RVC in a 10 minute window, it might become a flicker issue. Recloser schemes and advanced distribution automation strategies will significantly change the number of rapid voltage changes.

4) Harmonic distortion

It is possible that both the current and voltage *THD* values in the MV and LV networks change following a reconfiguration, for a number of reasons. Variation in fault level as a consequence of switching arrangements is unlikely to be a major contributor, especially at the MV level. It is more likely that reconfiguration may introduce a different mix of loads that could either improve or worsen the current *THD* (*ITHD*) and subsequently the voltage *THD* (*VTHD*).

Reconfiguration can also lead to an excessive number of transformer energisations during restoration following a fault, which should be avoided to minimize the level of second harmonic distortion. The possibility of ferroresonance is low, since the energisations will likely be on loaded transformers. It is more likely that transients will occur and will last for longer periods, since the network load may be changing towards lower resistance.

5) Local frequency variation

In a network with high DER penetration, some of the DERs may be disconnected from the network following a fault. During periods of high DER generation, this might result in local variation in system frequency. This is an evolving issue and distribution system is not presently equipped to control system frequency, and depends on the bulk-power system for load-generation balance. Future distribution management systems (DMS) are expected to have effective means for controlling system frequency to accommodate high penetration of DERs [31].

6) Other PQ impacts

Some other PQ impacts include:

- Change in current unbalance due to load re-arrangement or single-phase tripping or reclosing operations.
- Change in the resonant frequency of the MV and LV networks. For example, the relative positions of power factor correction (PFC) capacitors may be altered following a reconfiguration.
- Loss of "visibility" of PQ performance due to reconfigurations, which also change the relative position of sensors in the distribution network.

VII. DEMAND-SIDE MANAGEMENT

Demand Side Management (DSM) is defined [36] as: *"A set of measures, actions and interventions, initiated deliberately and with specific purpose by end-users, or* *network operators, or a third party (e.g. energy suppliers), aimed at changing, restructuring and/or rescheduling power demands of a group of loads, load sector(s), part of a system, or a whole system, in order to produce desired changes in the actual amounts and/or time-patterns of power demands supplied at the dedicated point(s) of delivery for end-use consumption of electricity."*

PQ concerns related to the implementation of two general types of DSM are discussed and illustrated in further text.

A. Energy Efficiency and Energy Conservation DSM

This type of DSM is related to programs in which less-efficient types of equipment are being systematically replaced, declared "obsolete", or even (effectively) banned for sale, in order to allow for a wider scale implementation of more energy-efficient equipment. Examples are phasing out of incandescent lamps and incentivized switching to CFLs and LED lamps, as a part of a recent EU "Eco Design Directive", [37]. These DSM schemes also include technical or technology improvements of various types of electrical equipment, typically occurring over longer time-scales (e.g. replacement of CRT TVs with LCD TVs).

The potential impact of this type of DSM on PQ, especially the impact of the mass-replacement of incandescent lamps by electronic equivalents, has been studied by several authors. Simulations are presented for example in [38] and measurements in [39, 440]. An overview of both simulations and measurements is presented in [41], where it is concluded that the simulations generally predict a higher increase in distortion due to replacement of incandescent lamps by CFLs than shown by measurements. Further studies should, among others, be aimed at explaining this discrepancy.

B. Direct DSM Control

In these DSM schemes, specific types of electrical equipment are controlled (usually switched off and on), either by customers or by network operators, or by a third party on their behalf (e.g. aggregators or energy suppliers). This feature is also known as demand response (DR) in some parts of the world [42]. This type of DSM is typically aimed at reducing system peak load, or implemented as a part of network balancing mechanism, or implemented to realize certain system support capabilities, or to provide different types of system reserve (primary, secondary, frequency response, etc.). Although these DSM schemes are generally directed towards improving network performance (including PQ), there are specific applications which are using DSM for other purpose (e.g. as a part of microgrid controls discussed in Section IV).

An example of the potential impact of this type of DSM on PQ is illustrated in Fig. 1, showing impact of a group connection/disconnection of EV chargers on a negative sequence voltage unbalance, measured in a German LV network [43].

The connection of single-phase chargers to three-phase power supply systems can cause significant unbalance in terms of fundamental voltages and currents. Even if the charging points are equally distributed on all three phases, an impact on unbalance is possible due to the different charging behavior of customers and differences in actually connected EV chargers. A field study in [43] has shown that a connection of 10 EVs in the same phase, each drawing a charging current of around 16 A, can result in unbalance values exceeding the currently prescribed compatibility level (2% in [44]). Even if charging points are uniformly distributed on all three phases, the impact of the 10 EVs on unbalance is visible. Especially during the evening hours, unbalance values of up to 1.6% are observed, Fig. 1.

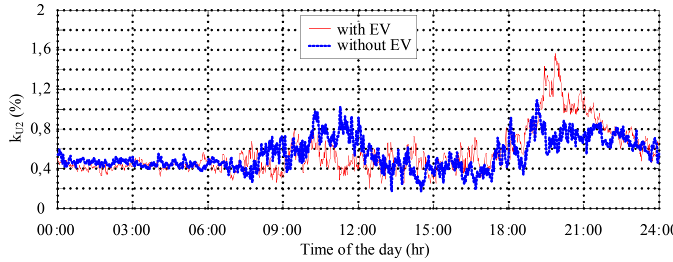

Fig. 1. Impact of a group-connection of EV chargers on negative sequence voltage unbalance, [43].

C. PQ Concerns Related to DSM

Main PQ concerns related to a large-scale implementation of DSM schemes in smart grids include [38, 45, 46]:

- Connecting and disconnecting large amounts of same or similar types of loads might change network characteristics and impact grid performance, for example through higher levels of harmonics, unbalances or more pronounced voltage variations.
- The load recovery period after DSM-based load reconnection will be associated with a higher than usual consumption (and hence lower voltages) and possibly also higher levels of harmonic emission.
- Disconnecting specific types of load might remove certain harmonic cancellation effects, again causing temporary increase of harmonic emission. For example, disconnecting a large resistive electric heating load may significantly reduce the damping and result in considerably higher distortion levels, if resonance frequencies are close to harmonic frequencies.
- More frequent switching of DSM-enabled groups of loads will lead to a higher number of voltage steps, requiring more voltage control actions and possibly resulting in a more frequent unintentional tripping of sensitive equipment
- The communication between the network operator and the controlled devices, including DSM-loads, will, at least partly, make use of the wires in the power grid. This power-line communication will result in higher voltage distortion and complex interactions will occur, where communication signals may adversely impact equipment and where emission and impedance of equipment may impact the communication [47].
- Also economic incentives in the form of short-term (e.g hourly) markets can result in the simultaneous switching of large numbers of devices. For example, in a network with small combined-heat-and-power plants (μCHPs), these units may switch on almost at the same time, if the electricity

price exceeds a certain threshold.

VIII. Recommendations

The mapping of the adverse consequences, as presented in the previous sections, is in this section used as a basis for formulating a set of recommendations, which are also discussed in terms of the required changes in standards and regulations.

A. Need for further studies and data collection

Many of potential adverse impacts are not well-understood, in part because the details of the future technology are currently often not known. More studies are therefore needed towards quantifying the impact of smart-grid applications on PQ.

Doing measurements in VVC schemes is certainly encouraged, but as the number of schemes remains limited, and because very high overvoltage values may only occur in very specific situations, simulation studies should be done in parallel with those measurements.

Studies are needed to get a better understanding of origin, propagation and impact of waveform distortion in the range from 2 kHz to 150 kHz.

Further investigations are also needed to be able to predict the impact of new types of equipment on harmonic distortion levels. The discrepancy between the results for the introduction of CFLs and LED lamps, from measurements and simulations needs to be explained.

The power quality issues occurring in AC microgrids during islanded operation and in DC microgrids should be investigated.

An essential part of future PQ studies is the large-scale data collection through local and global monitoring systems, including their integration with the system state estimators. It is expected that state estimation will play a critical role in the future distribution networks [48]. Existing data collection (e.g. through power quality monitors, protection relays and smart meters) should be combined with additional data collection, in order to get an overview picture of the PQ and to detect trends in PQ associated with new technologies. Gathering PQ data should also be an integral part of all demonstration projects within smart distribution grids.

B. Damping at harmonic frequencies

The increased use of the power-electronic converters as part of end-user equipment for introducing damping at harmonic frequencies, should be seriously studied.

Studies are needed to quantify the damping provided by LV and MV networks and equipment connected to these networks. Such studies should include both simulations and measurements. Quantitative information is also needed for estimating the amplification of harmonic levels due to resonances and also to estimate the overvoltages due to capacitor energizing.

C. New power quality indices

New indices should be introduced in standards and regulation for analyzing the new power-quality phenomena. This includes methods to quantify emissions in the frequency range from 2 kHz to 150 kHz; and methods to quantify number and severity of voltage steps.

New PQ indices are also needed to quantify the voltage quality during islanded operation of AC microgrids and DC microgrids, during the transitions between islanded and grid-connected operation, and during feeder reconfiguration after a fault.

D. Improved smart-grid control methods

Smart-grid control methods should include in their control algorithms phenomena like harmonics and short-duration variations in voltage magnitude. With feeder reconfiguration and with advanced voltage control, the occurrence of harmonic resonances should be observed and where possible predicted. High harmonic levels due to resonances should be avoided.

E. Rapid voltage changes and switching transients

Guidelines are needed, for use in standards and regulations, on what are acceptable sizes and numbers of voltage steps (rapid voltage changes) in smart distribution networks.

The impact of repeated switching transients on end-user equipment should be investigated. Adding damping, either in the form of resistive part of passive filters, or by means of active filters, should be further investigated.

With the expected increase in number of (individual) RVC, it is important to have a generally accepted standardized method for their measurement. Such a method is part of the latest version of IEC 61000-4-30. More experience with the use of these measurement methods is needed.

Standardized indices should be developed, including second-harmonic distortion levels after transformer energizing.

F. Equipment Compatibility

Some of the smart distribution-grid applications introduce new types of disturbances, or result in increased levels of existing ones. This requires a standardization effort towards new and improved emission and immunity levels to ensure a continued high probability of electromagnetic compatibility between the grid and equipment connected to it.

IX. Conclusions

This paper considers and maps expected and possible adverse consequences for PQ of introducing smart distribution-grid technologies and applications. The mapping is to a large extent based on the experience and knowledge of power quality and smart grid experts in an international joint working group: CIGRE/CIRED JWG C4.24. Additional information from available literature and from field studies is also used for a more detailed discussion, providing illustrations of characteristic cases and some practical examples. Finally, some recommendations for further work and research are provided, as well as a discussion of required changes in standards and regulation.

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The opinions expressed in this paper may deviate from the ones of the working group, from CIGRE and from CIRED.

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